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Analysis of input harmonic current mitigating performance in dual output phase-shift distribution transformer

Guo Jian[1] Lin Heyun[2] Fang Shuhua[2]

([1]School of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China)

([2] School of Electrical Engineering, Southeast University, Nanjing 210096, China)

Abstract: A novel dual output phase-shift distribution transformer (DOPSDT) is proposed based on the electromagnetic filtering theory. First, its structural characteristics, winding connection mode and turn number ratio for special phase shifting are investigated. Secondly, the balance formulation of harmonic magneto-motive forces is derived and the electromagnetic filtering principle of the DOPSDT is introduced. The harmonic mitigating performance under different nonlinear load conditions are also analyzed using the field-circuit coupled method. The analysis results show that the DOPSDT can mitigate the primary current distortion even under severe nonlinear load conditions. By applying the zero sequence flux cancellation and phase-shift techniques at their secondary windings, the DOPSDT can significantly reduce the 3rd, 5th, 7th, 9th, 15th, 17th and 19th harmonics within its secondary windings.

Key words: shift-phase transformer; harmonic mitigating; electromagnetic filtering; field-circuit coupled method

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With the extensive application of power electronics equipment, electrical systems with conventional transformers are generally not suited to handle the harmonics generated by nonlinear loads. First, due to the electromagnetic coupling among the windings, the secondary harmonic current flows into the upstream system and affects the security of the power system. Secondly, triple harmonic currents (3rd, 9th and 15th) circulating in the primary delta windings of the transformer increase voltage distortions and power losses[1-5].

In order to address the harmonics generated by nonlinear loads, this paper presents a new dual output phase-shift distribution transformer (DOPSDT) using the phase-shift technique. The transformer structure characteristics, the winding connection mode and the turn number ratio for a special phase shift are investigated. To verify the effectiveness of the DOPSDT mitigating harmonics, a field-circuit coupled model is proposed to simulate the harmonic mitigating performance of a 20 kV · A DOPSDT under different nonlinear loads.

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Biography: Guo Jian(1980—), male, doctor, lecturer, nuaaeelab_gj@nuaa. edu. cn.

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1 Structure Feature

1.1 Winding connection mode and structure layout

The DOPSDT has a primary three-phase winding and two secondary three-phase windings with the neutral line. The primary winding of the DOPSDT is delta-connected and the secondary winding connection diagram is shown in Fig. 1(a). In the secondary winding, the zig-zag connection is used to reduce the zero-sequence flux and impedance. Fig. 1 (b) is the turns match diagram. The winding turns meet $W_{11} = W_{12} = 1.732N_2$ in the first secondary winding (A_1) and $W_{21} = 2W_{22} = 2W_{23} = 2N_2/3$ in the second (A_2), where N_2 is the equivalent turns of the secondary winding. As a result, there exists a 30° phase difference between the output voltages of the two secondary windings as shown in Fig. 1(c).

In order to reduce transformer harmonic impedance and output voltage distortions, a radial split layout is employed in the two secondary windings. The structure layout of each phase winding is shown in Fig. 2.

1.2 Mitigating harmonic current mechanism

When the zero sequence current flows through the secondary windings, the magneto motive forces (MMFs) of the two groups of output windings are

$$\left.\begin{aligned} F_{21} &= I_{21}(W_{11} - W_{12}) = 0 \\ F_{22} &= I_{22}(W_{21} - W_{22} - W_{23}) = 0 \end{aligned}\right\} \qquad (1)$$

where F_{21} is the MMF of the first secondary winding; F_{22} is the MMF of the second secondary winding; I_{21} is the current of the first secondary winding; I_{22} is the current of the second secondary winding.

Because the MMFs equal zero, the zero sequence flux is cancelled within the secondary windings of the DOPSDT and this prevents zero sequence current from coupling to the primary winding as in a delta-wye transformer.

There is a 30° phase shift angle between the two groups of output windings which destroys the balance of some

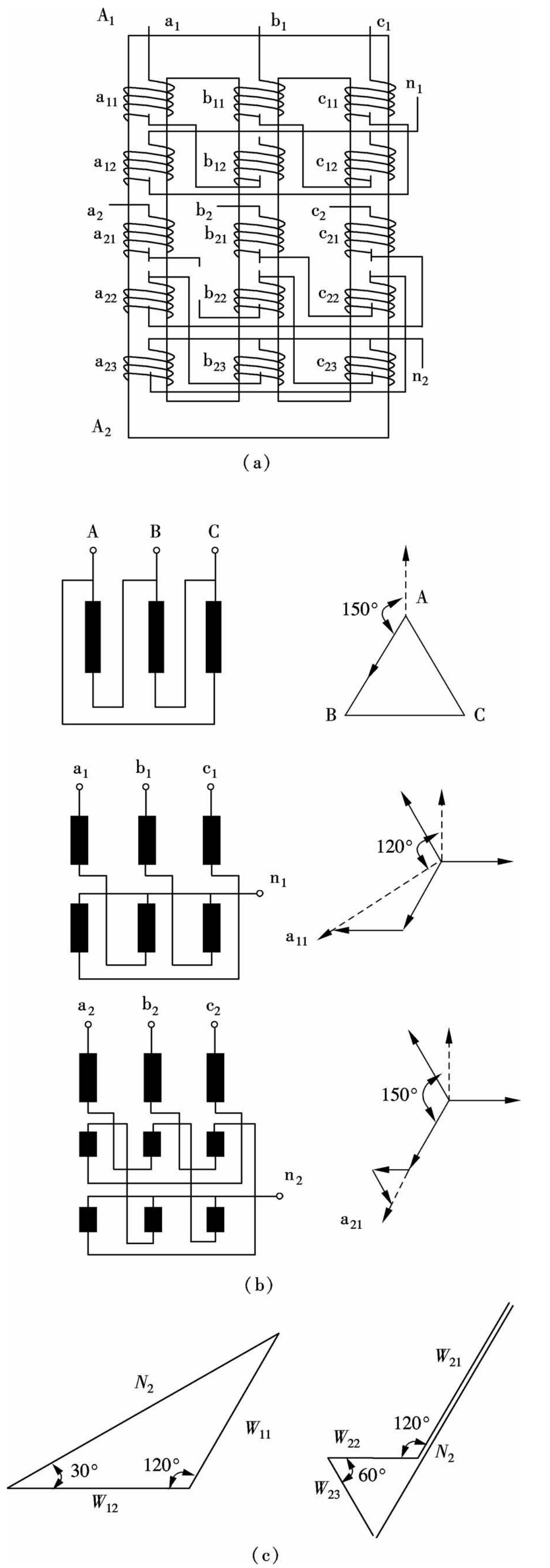

Fig. 1 DOPSDT winding connection mode. (a) Secondary windings connection diagram; (b) Secondary winding turns match diagram; (c) Input and output voltage vector diagram

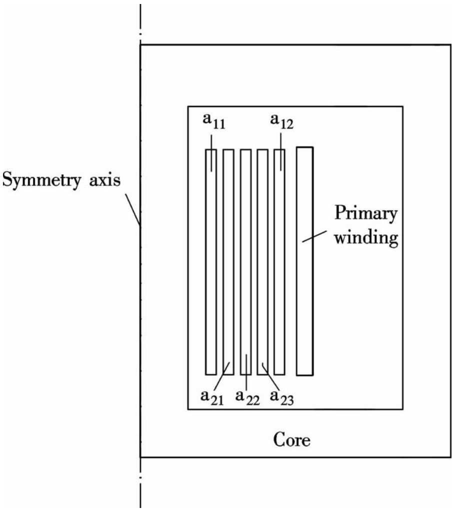

Fig. 2 Transformer winding structure layout

specific harmonic fluxes so that they are not coupled to the primary winding. When the harmonic current flows through the secondary windings, the MMFs of the two groups of output windings are

$$\left.\begin{aligned} F_{21} &= I_{21}\left[W_{11}\sin(2\pi kft) - W_{12}\sin\left(2\pi kft + \frac{2\pi}{3}k\right)\right] \\ F_{22} &= I_{22}\left[W_{21}\sin\left(2\pi kft - \frac{\pi}{6}k\right) - W_{22}\sin\left(2\pi kft - \frac{\pi}{6}k + \frac{2\pi}{3}k\right) - \right. \\ &\quad \left. W_{23}\sin\left(2\pi kft - \frac{\pi}{6}k - \frac{2\pi}{3}k\right)\right] \end{aligned}\right\} \tag{2}$$

where k is the k-th harmonic.

It is noted that the 5th, 7th, 17th and 19th harmonic MMFs of the two groups of output windings are opposite. The more balanced the nonlinear loads between the two outputs, the more effective the harmonic cancellation.

2 Coupled Field-Circuit Formulation

The harmonic mitigating performance of the designed 20 kV · A DOPSDT is analyzed by the field-circuit coupled method proposed[6-10]. Fig. 2 is the transformer axisymmetric model for calculating the flux leakage field and phase A, phase B and phase C should be simultaneously analyzed by the proposed model. Fig. 3 is the DOPSDT winding equivalent circuit model of Fig. 2.

The axisymmetric static magnetic field of the DOPSDT is analyzed by the FEM. The magnetic vector potential $\boldsymbol{A}_{\mathrm{R}}$ is governed by the classical Poisson equation as follows:

$$\left.\begin{aligned} &\frac{\partial}{\partial r}\frac{1}{\mu}\frac{1}{r}\left(\frac{\partial \boldsymbol{A}_{\mathrm{R}}}{\partial r}\right) + \frac{\partial}{\partial z}\frac{1}{\mu}\frac{1}{r}\left(\frac{\partial \boldsymbol{A}_{\mathrm{R}}}{\partial z}\right) = -J_{\theta} && \text{in } \Omega \\ &A_{\theta} = 0 && \text{on } L \end{aligned}\right\} \tag{3}$$

where μ is the permeability and J_{θ} is the current density.

Taking each winding part as an independent circuit, the matrix equation of the winding circuit is

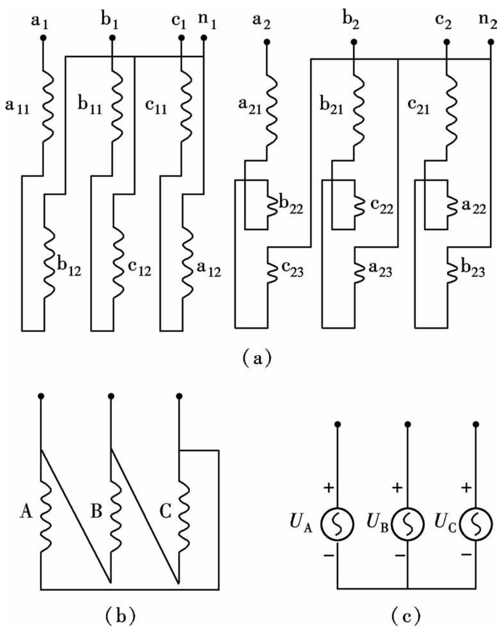

Fig. 3 Equivalent circuit model. (a) Secondary winding equivalent circuit; (b) Primary winding equivalent circuit; (c) Source equivalent circuit

$$\boldsymbol{U} = \frac{\mathrm{d}\boldsymbol{\Psi}}{\mathrm{d}t} + \boldsymbol{RI} \tag{4}$$

where $\boldsymbol{U}$ is the voltage vector; $\boldsymbol{\Psi}$ is the flux linkage; $\boldsymbol{R}$ is the winding resistances; and $\boldsymbol{I}$ is the current.

Discretizing (3) in space and coupling with Eq. (4), the field circuit coupled global equation can be given as

$$\begin{bmatrix} \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{G}_1 & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{G}_{21} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{G}_{22} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{A}}_R \\ \dot{\boldsymbol{I}}_1 \\ \dot{\boldsymbol{I}}_{21} \\ \dot{\boldsymbol{I}}_{22} \end{bmatrix} + \begin{bmatrix} \boldsymbol{K} & \boldsymbol{D}_1 & \boldsymbol{D}_{21} & \boldsymbol{D}_{22} \\ \boldsymbol{0} & \boldsymbol{R}_1 & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{R}_{21} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{R}_{22} \end{bmatrix} \begin{bmatrix} \boldsymbol{A}_R \\ \boldsymbol{I}_1 \\ \boldsymbol{I}_{21} \\ \boldsymbol{I}_{22} \end{bmatrix} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{U}_1 \\ \boldsymbol{U}_{21} \\ \boldsymbol{U}_{22} \end{bmatrix} \tag{5}$$

where $\boldsymbol{K}$ is the stiffness matrix; $\boldsymbol{G}$ is a matrix depending on the geometrical features of the windings; $\boldsymbol{D}$ is a matrix similar to $\boldsymbol{G}$; $\boldsymbol{U}_1$ is the vector of primary voltage; $\boldsymbol{U}_{21}$ and $\boldsymbol{U}_{22}$ are the vectors of output voltage; $\boldsymbol{I}_1$ is the vector of primary current; $\boldsymbol{I}_{21}$ and $\boldsymbol{I}_{22}$ are the vectors of output current; $\boldsymbol{R}_1$ is the resistance of the primary winding; $\boldsymbol{R}_{21}$ and $\boldsymbol{R}_{22}$ are the resistances of the secondary winding.

3 Calculation Results and Analysis

3.1 Zero sequence magnetic field distribution

When the zero-sequence current flows through the first secondary winding, and at the same time the primary winding and the second secondary winding are short circuits, the magnetic field distribution is shown in Fig. 4 (a). Fig. 4 (b) is the magnetic field distribution when the zero-sequence load current flows through the second secondary winding, and at the same time the primary winding and the first secondary winding are short circuits. The flux only links with the secondary winding, so the primary winding cannot induce the triple harmonic currents.

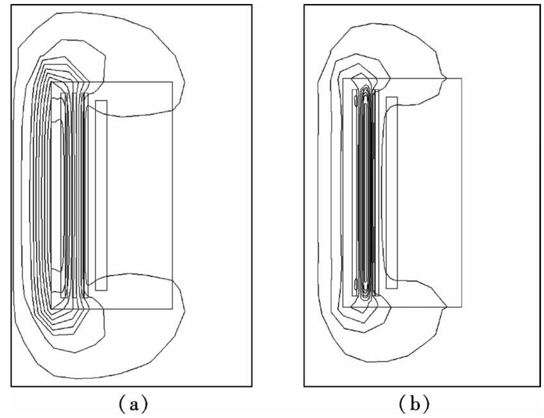

Fig. 4 Zero sequence magnetic field distribution. (a) Zero sequence current flows through the first output winding; (b) Zero sequence current flows through the second output winding

3.2 Phase-shift angle of output voltage

When the primary winding is energized to carry the rated voltage and both the secondary windings are open-circuited, the output voltage waveforms of the secondary windings are shown in Fig. 5. There is a 30° phase shift angle between the two outputs, which verifies the validity of the turns match relationship of the secondary windings of the DOPSDT.

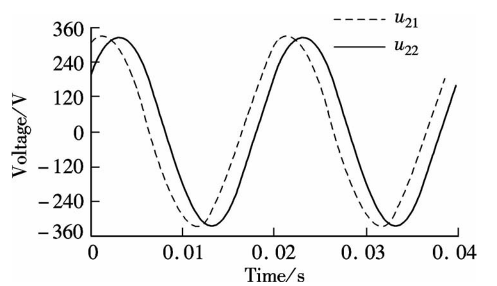

Fig. 5 Output voltage under open-circuit condition

3.3 Harmonic mitigating performance verification

In order to verify the DOPSDT harmonic mitigating performance, the primary winding is energized to carry the rated voltage and the secondary side output of each phase winding is connected to a typical nonlinear load as shown in Fig. 6. The power factor of the load Z_1 and Z_2 are 0.8, and the rate load is Z_e.

The current total harmonic distortion can be given by

$$I_{\mathrm{THD}} = 2\sqrt{\sum_{n=3}^{21} I_n^2} \tag{6}$$

$$I_n = \frac{I_n}{I_1} \times 100\% \qquad n = 1, 3, \cdots \tag{7}$$

where I_n is the current at the harmonic number n.

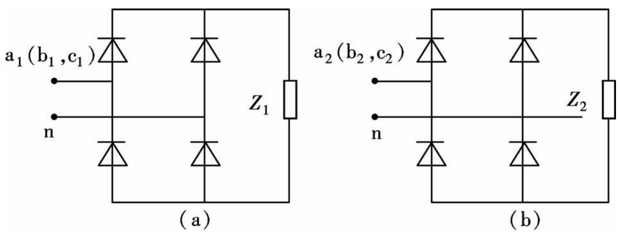

Fig. 6 Typical nonlinear load circuit. (a) The first output load circuit; (b) The second output load circuit

Fig. 7 shows the secondary windings current waveforms and harmonic spectrums when the load meets $Z_1 = Z_2 = Z_e$. It can be seen that the rectifier loads produce flat-topping currents which contain the 3rd, 5th, 7th, 9th and higher harmonics by analyzing the current time domain waveforms. Compared with the secondary currents, the primary current is approximately a sine wave without the 3rd, 5th, 7th, 9th 15th, 17th, 19th and 21st harmonics. By electromagnetic filtering, the DOPSDT treats the 3rd, 5th, 7th, 9th, 15th, 17th and 19th harmonics within its secondary windings and reduces the loads of the primary windings.

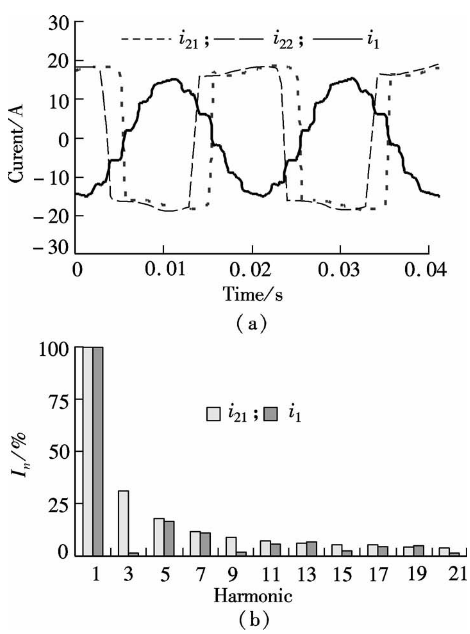

Fig. 7 Harmonic waveforms and spectrums under $Z_1 = Z_2 = Z_e$. (a) Current waveforms; (b) Harmonic spectrums

Tab. 1 lists the harmonic distortions on the primary and the secondary windings under different load conditions. For the most effective harmonic cancellation, the nonlinear loads should be approximately balanced between the two secondary outputs. However, as shown in Tab. 1, excellent results can be achieved even when the loads cannot be well balanced.

Tab. 1 Harmonic contents on the primary and secondary windings under different load conditions %

Load conditions	Harmonic distortion		
	$I_{22\text{thd}}$	$I_{21\text{thd}}$	$I_{1\text{thd}}$
$Z_1 = Z_e, Z_2 = \infty$	40.5		22.7
$Z_1 = Z_e, Z_2 = 2Z_e$	41.2	44.4	11.4
$Z_1 = Z_2 = Z_e$	40.8	40.8	7.9

4 Conclusions

Based on the theory of electromagnetic filtering, this paper presents a new DOPSDT and investigates its structural characteristics, winding connection mode and turn number ratio for special phase shifting. The harmonic mitigating performance of a designed 20 kV · A DOPSDT is analyzed by the field-circuit coupled method. This research shows that

1) The zig-zag connection mode of the DOPSDT secondary windings can weaken the zero sequence flux and prevent zero sequence current from coupling to the primary winding.

2) When the first secondary windings meet $W_{11} = W_{12} = 1.732N_2$ and the second meet $W_{21} = 2W_{22} = 2W_{23} = 2N_2/3$, there is a 30° phase shift angle between the two outputs which cancels the balanced portion of the 5th, 7th, 17th and 19th harmonic fluxes so that they are not coupled to the primary winding.

3) The DOPSDT can provide extremely low primary current distortions even under severe nonlinear load conditions. For the most effective harmonic cancellation, the nonlinear loads should be approximately balanced between the two outputs.

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双输出移相配电变压器输入谐波电流抑制特性分析

郭 健[1] 林鹤云[2] 房淑华[2]

([1] 南京航空航天大学自动化学院,南京 210016)
([2] 东南大学电气工程学院,南京 210096)

摘要:提出了一种基于电磁滤波原理的双输出移相配电变压器. 首先,研究了其结构布置特征、绕组联接方式及实现特定移相角的匝数匹配关系. 其次,推导了该变压器的谐波磁势平衡方程,论述了变压器实现电磁滤波的机理. 通过建立该变压器的场路耦合模型,对不同非线性负载情况下的谐波抑制特性进行了分析计算. 研究结果表明,在严重的非线性负载情况下,双输出移相变压器仍可以有效抑制一次侧绕组输入电流的谐波;结合零序磁通消除技术和相移技术,该变压器可以将配电系统中主要存在的 3,5,7,17 和 19 倍次谐波电流抑制在二次绕组中.

关键词:移相变压器;谐波抑制;电磁滤波;场路耦合
中图分类号:TM41